IPHA TECHNICAL SEMINAR 2017

October 25–26. Tallinn, Estonia

In-plane behaviour and horizontal actions

Joost Walraven
Delft University of Technology | The Netherlands

Organized by

IPHA
INTERNATIONAL PRESTRESSED
HOLLOWCORE ASSOCIATION

in cooperation with

BÜ eesti betooniühing

EESTI EHITUSINSENERIDE LIIT

supported by

fib CEB-FIP

Sponsored by TALOT StruSoft peikko group CONSOLIS E-BETOONELEMENT ECHO PRECAST ENGINEERING PROGRESS GROUP PRECAST SOFTWARE engineering betoneks TMB

In-plane behaviour of hollow core slab systems

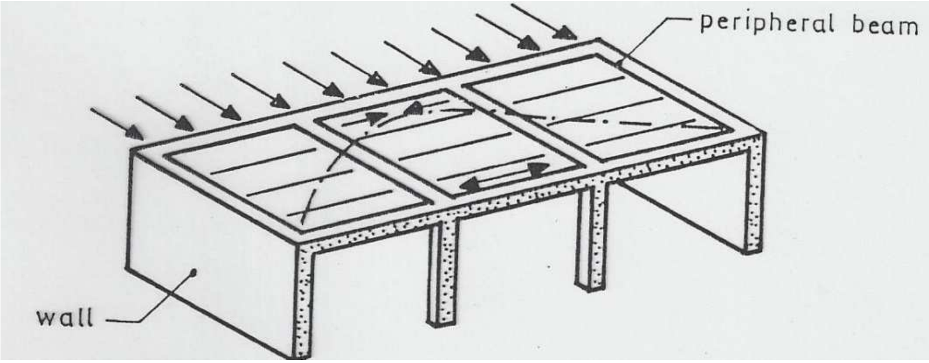
IPHA Technical Seminar
Tallinn, 25/26 October 2017

Em. Prof. Joost Walraven
Delft University of technology

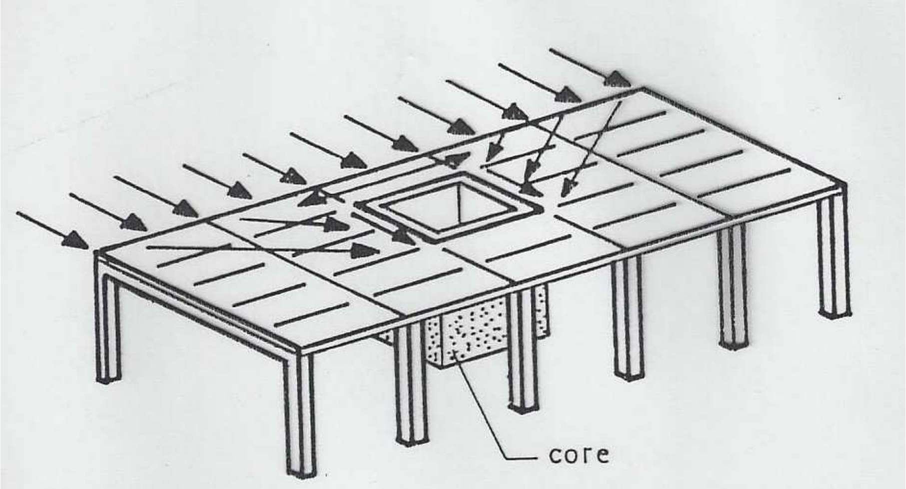
Delft University of Technology

Design models for diaphragm action

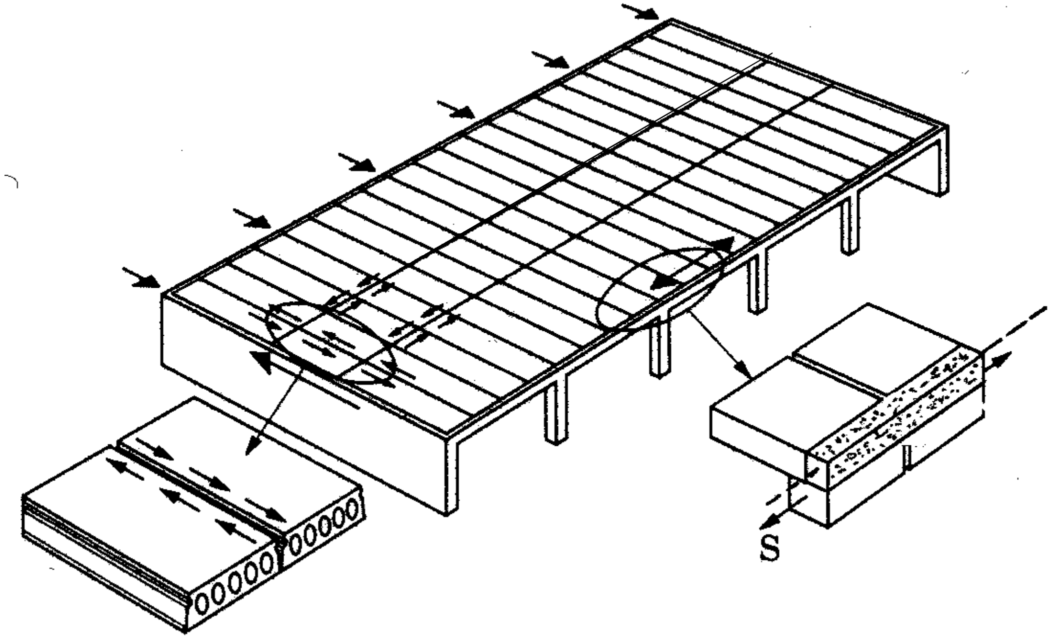
Arch action

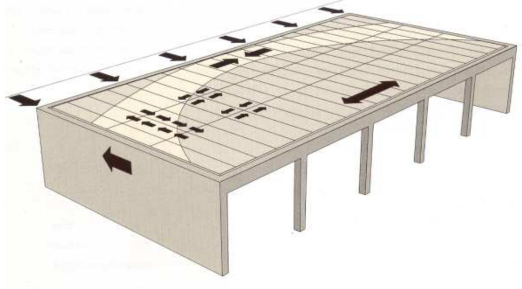


Strut and tie action



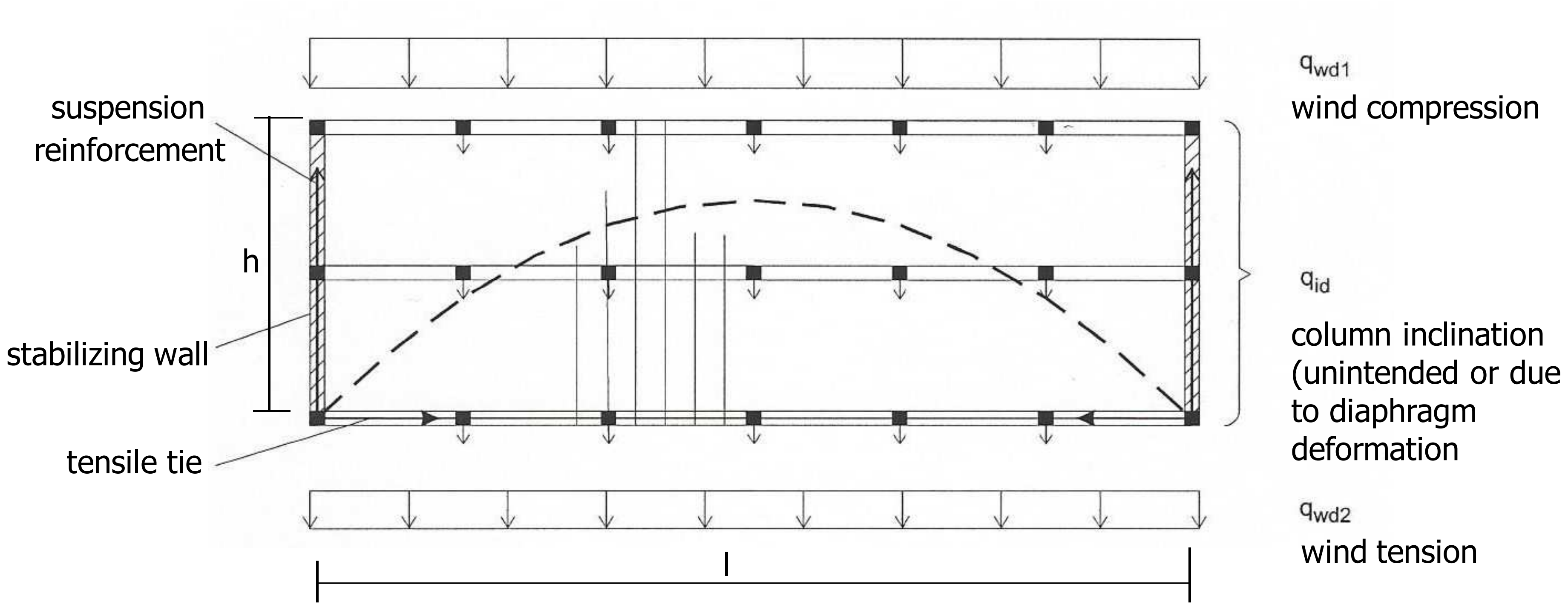
Design with hollow core slabs



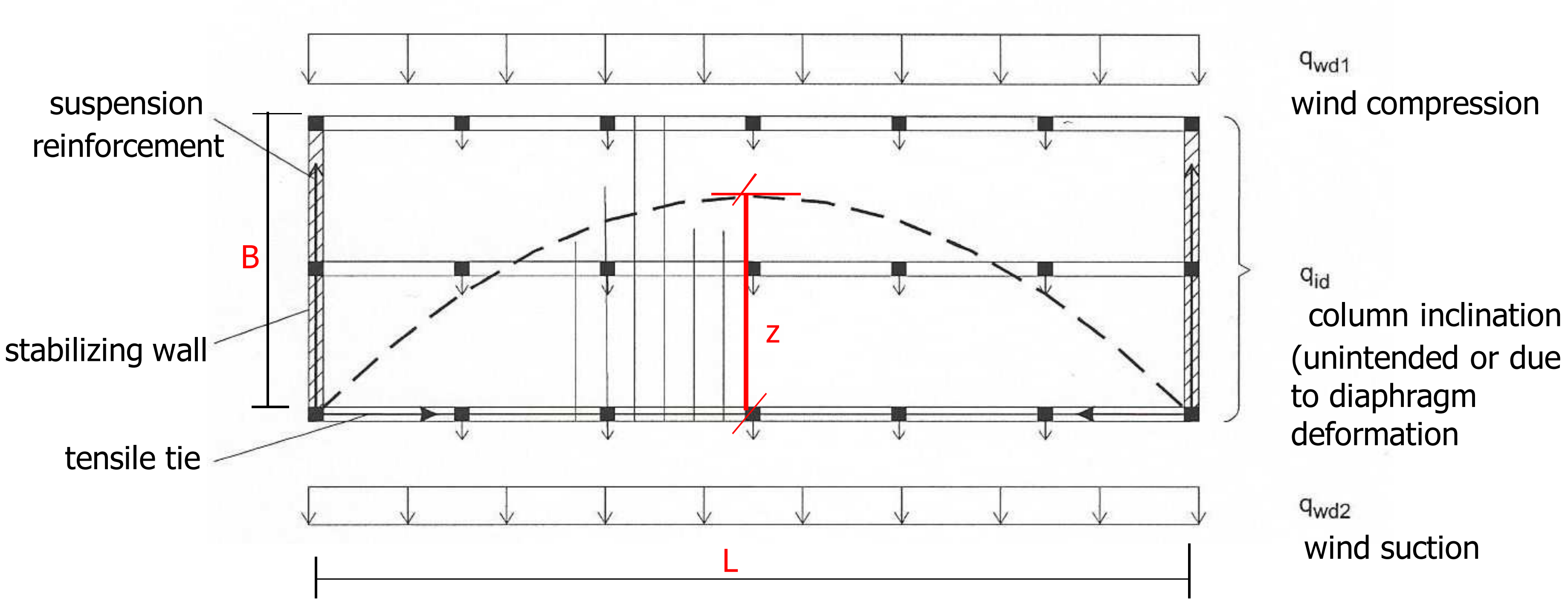


The assemblee of slabs should carry both the load in vertical direction and act as a diaphragm to transfer the horizontal loads on the structure to the stabilizing walls (and from there to the foundations).

Model of load transfer: arch action



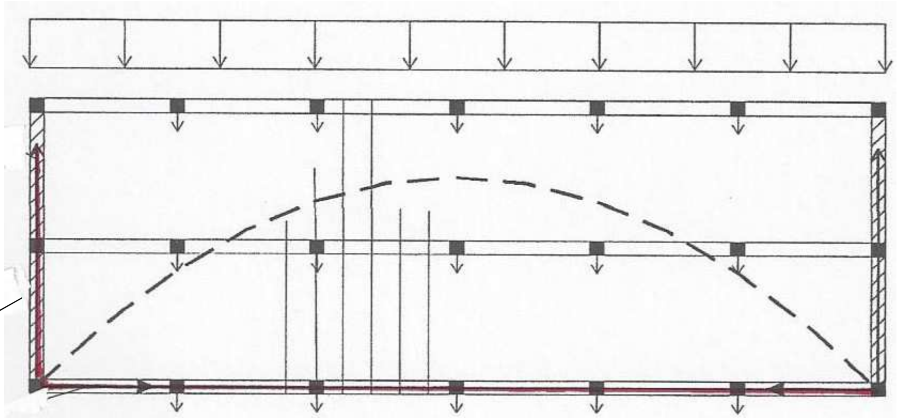
Model of load transfer: arch action



inner lever arm z depends on ratio B/L where $z = 0{,}8B$ for $B/L \leq 0{,}5$
$z = 0{,}5B$ for $B/L = 1$
interpolation for B/L in between

Delft University of Technology

Model of load transfer: arch action

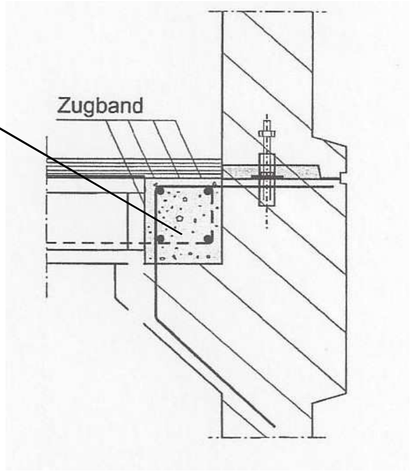


Suspension
reinforcement
in wall

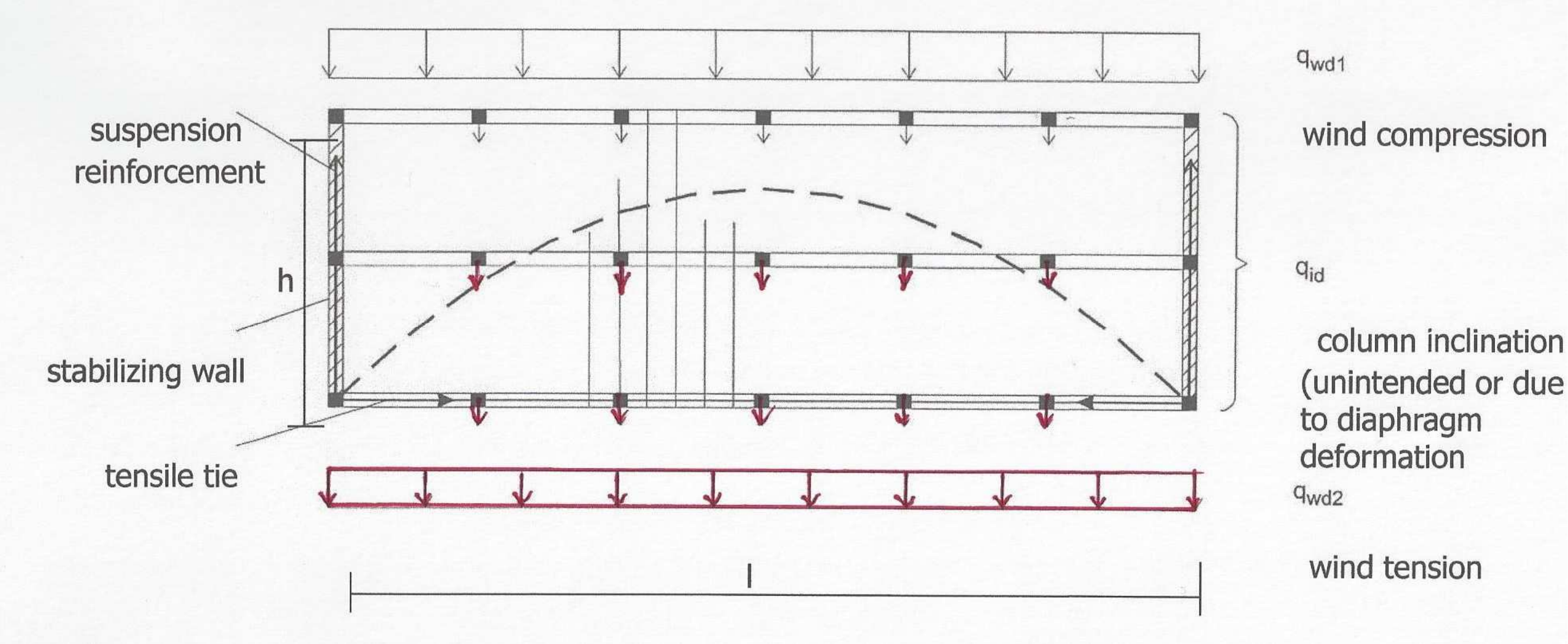
Connection wall - floor

Tensile tie
as a part of
edge beam

$$A_{s1} = M_{Ed}/(z \cdot f_{yd})$$

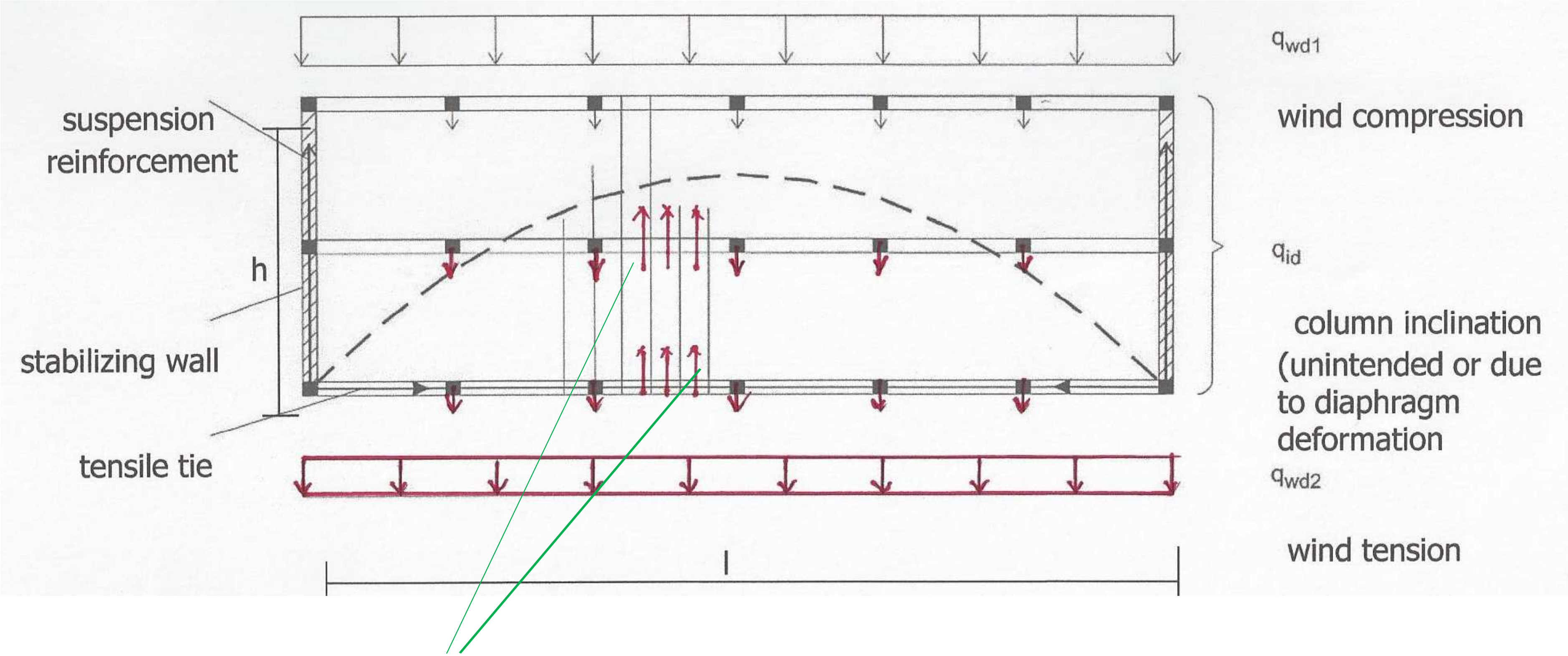


Suspension reinforcement to bring load to position above arch



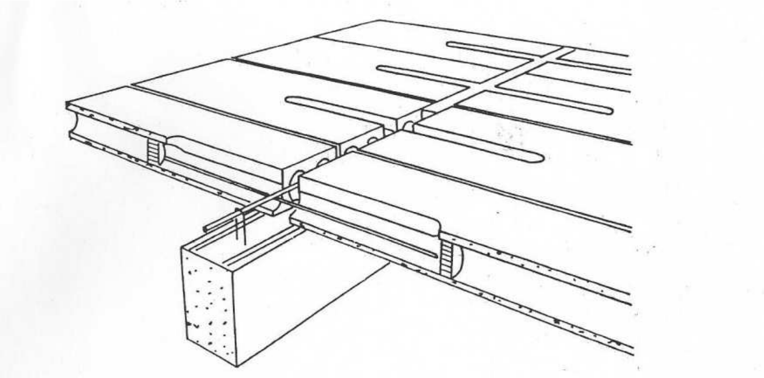
Loads due to wind tension and column inclination (in red colour) apply below the arch that should carry them. Therefore suspension reinforcement is required

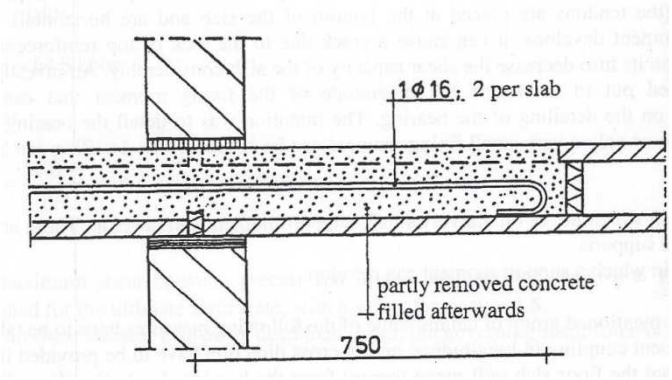
Suspension reinforcement to bring load to position above arch



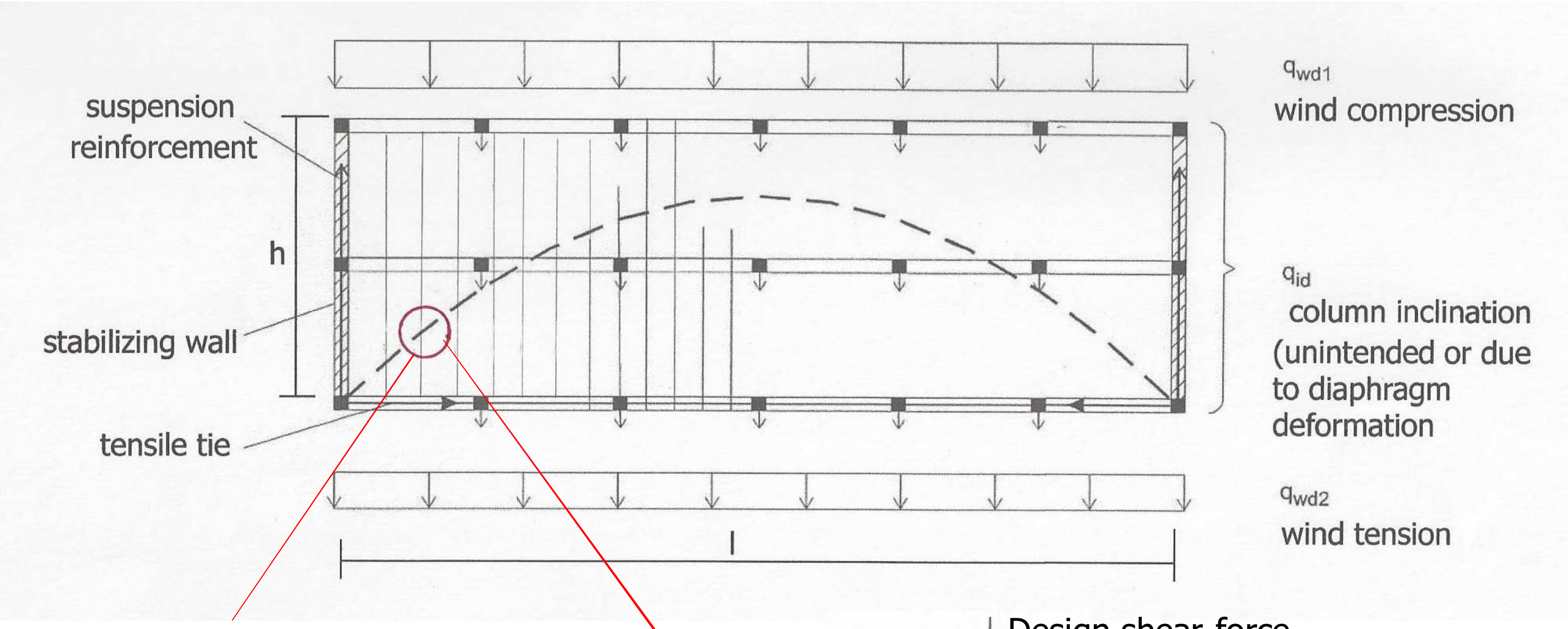
Coupling bars are provided at the end of the hollow core slabs in sleeves, creating tensile capacity through the slabs from bottom to top

Coupling bars in slabs in longitudinal direction to provide suspension capacity



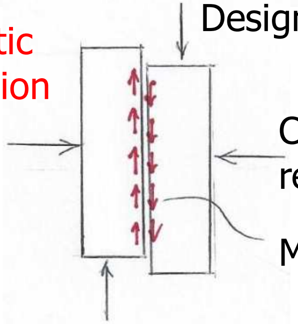


Shear capacity of joints between slabs



Simplified representation

More realistic representation

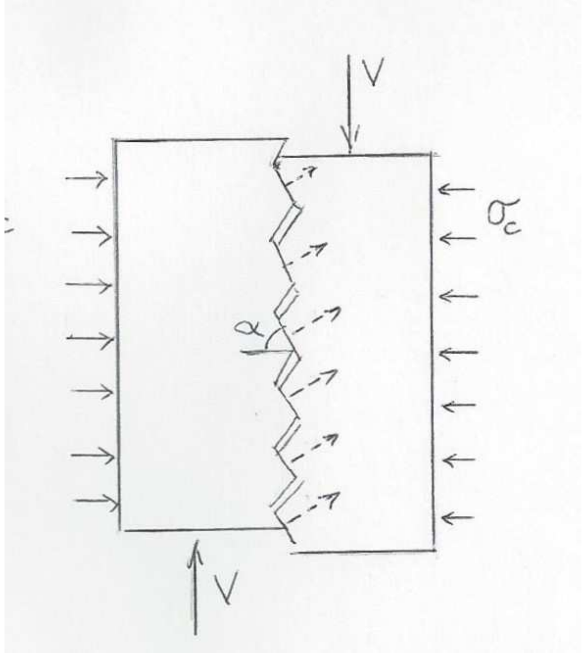


Design shear force

Clamping force generated by reinforcement

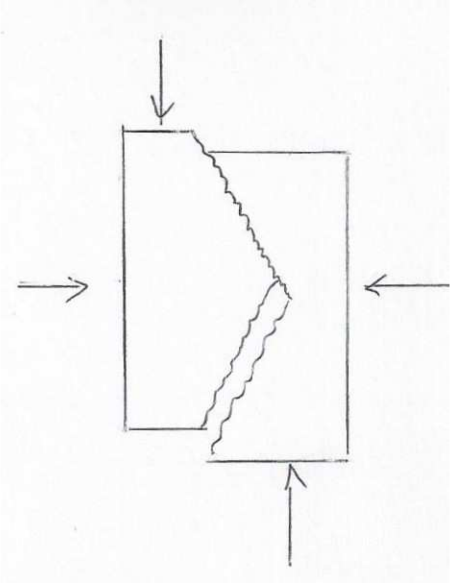
Mean shear stress

Principle of shear transmission across joints or rough interfaces



Original shear friction model (smooth saw teeths)

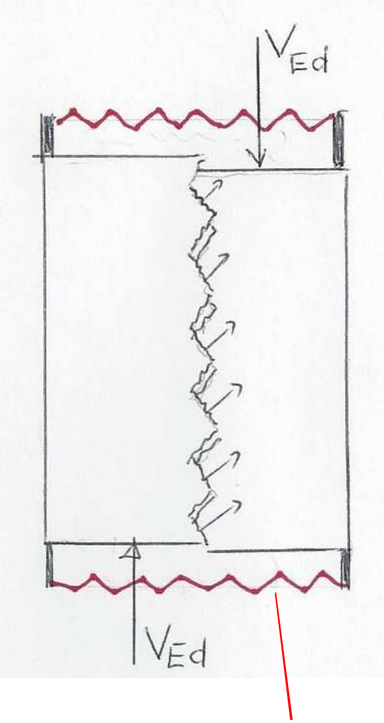
$$v_{Rd} = \sigma_c \tan\alpha$$



Improved shear friction model: saw teeths with micro roughness

$$v_{Rd} = c_0 + \sigma_c \tan\alpha$$

Principle of shear transmission across joints or rough interfaces



Maximum confining capacity of reinforcement

$A_s f_{yd}$

Shear friction model with confining reinforcement

$$v_{Rd} = c_0 + \rho f_{yd} \tan\alpha$$

or

$$v_{Rd} = c f_{ctd} + \mu \cdot \rho f_{yd}$$

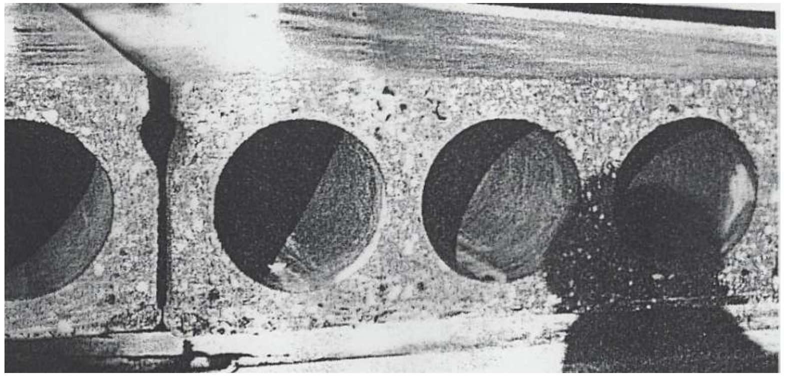
- f_{yd}: yield strength of steel
- ρ: reinforcement ratio
- μ: coefficient of friction depending on roughness
- f_{ctd}: Design tensile strength of concrete
- c: Coefficient depending on roughness
- v_{Rd}: Design shear strength of joint

Principle of shear transmission across joints or rough interfaces

Surface type	description	c	μ
Very smooth	Surface cast against formwork in steel,	0.025 - 0.10	0,5
smooth	Surface created by sliding formwork or extrusion, or free surface without treatment after vibration	0.20	0.6
rough	Profilation of at least Δh =3mm at Δl = 40mm	0.40	0.7
indented	Surface provided with keys	0.50	0.9

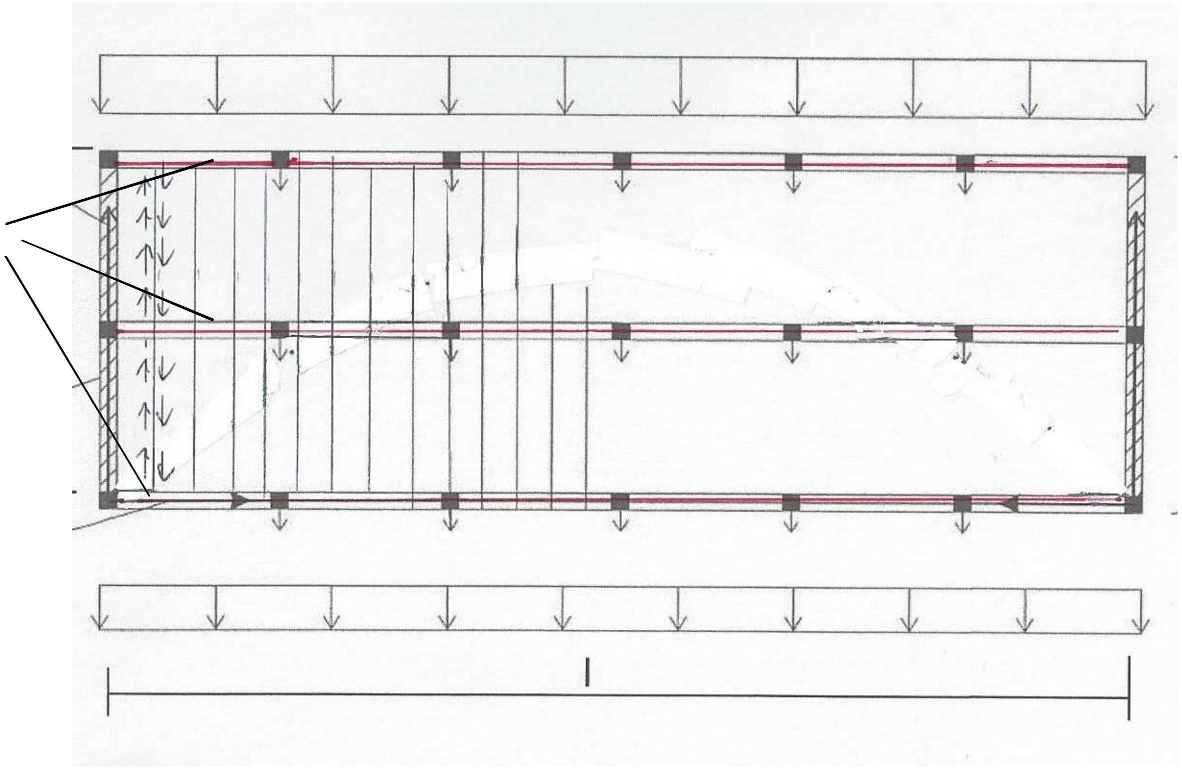
Parameters for interface shear according to EN 1992-1-1

Longitudinal joints with extruded faces



Category
”smooth”

Providing confining stresses in joints by transverse reinforcement to increase shear capacity



Transverse reinforcement providing confining action for generating sufficient shear capacity of joints

Shear resistance of edge beams can be added.

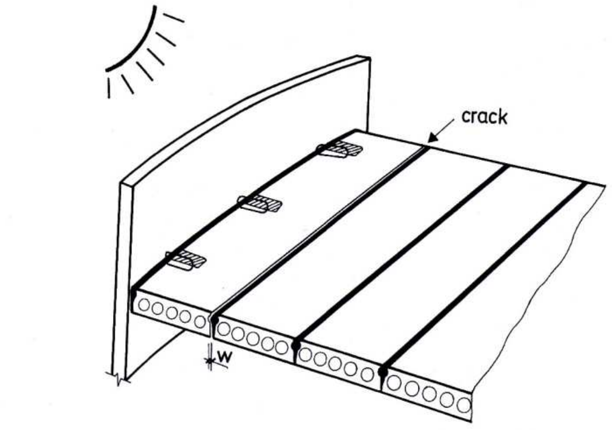
EN-1992-1-1 (Cl. 10.9.2.(12) limits the mean shear stress v_{Rdi} in the joint to 0.15 N/mm^2.

Large scale test at TU Delft for “demountable hollow core floors”

Hollow core floor with longitudinal joints made with a low strength mortar $f_c = 1\text{-}2\ \text{N/mm}^2$ in order to enable demountability

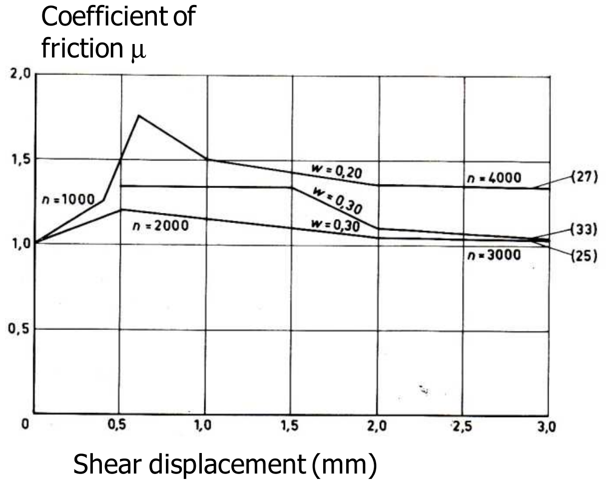
Design of slabs for diaphragm action

Verification of shear capacity of longitudinal grouted joints between hollow core slabs



Grouted joints in precast floors should normally be assumed to be cracked due to restraint stresses. Possibly also fatigue stresses occur due to wind Forces.

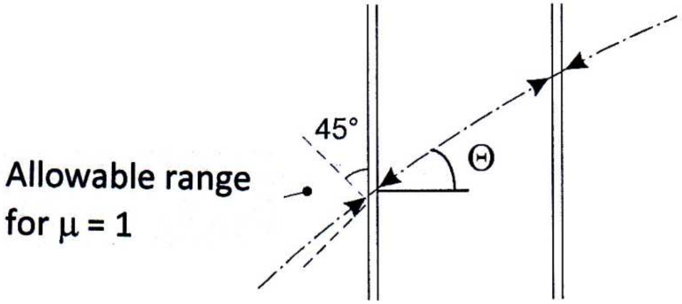
Shear test at cracked joint between two hollow core slabs (TU Delft), for very low strength mortar

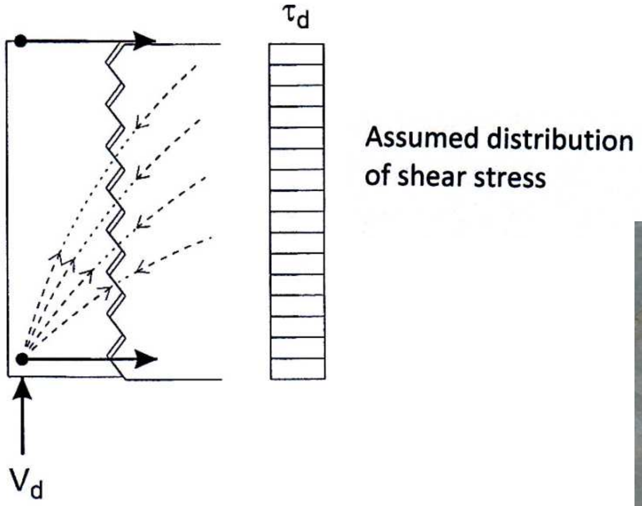


n = number of load cycles
w = initial crack width

Value μ > 1,0 holds true to at least up to 0,2 N/mm^2 even for a low strength mortar

Design of slabs for diaphragm action





Tests at TU Delft showed that no shear slip will occur if the friction angle is below μ = 1,0 even after thousands of load cycles.
If this is the case the following condition should be satisfied:

$$V_{Ed} / A_s f_{yd} \leq 1{,}0$$

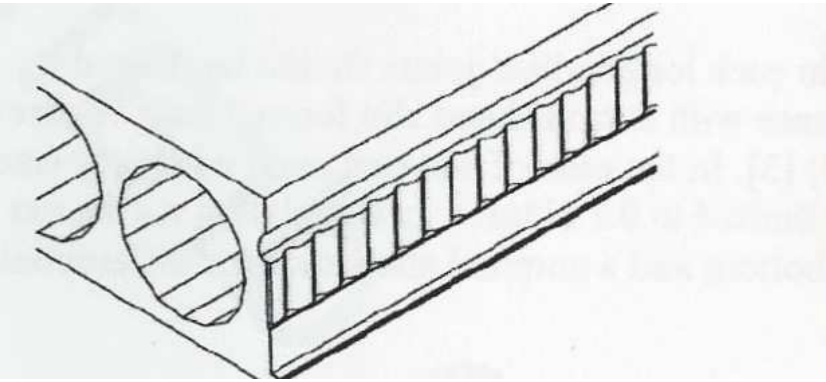
Where V_{ed} = design shear force in critical joint
A_s = cross sectional area of reinforcement intersecting the joint.
f_{yd} = design yield stress of reinforcement

Shear test at joint between two hollow core slabs (TU Delft)

Particular observation

If the joint cracks due to restrained shrinkage or bending, the crack creates keys, because of the variability of the interface strength in the joint faces

Increasing the shear capacity of the joints

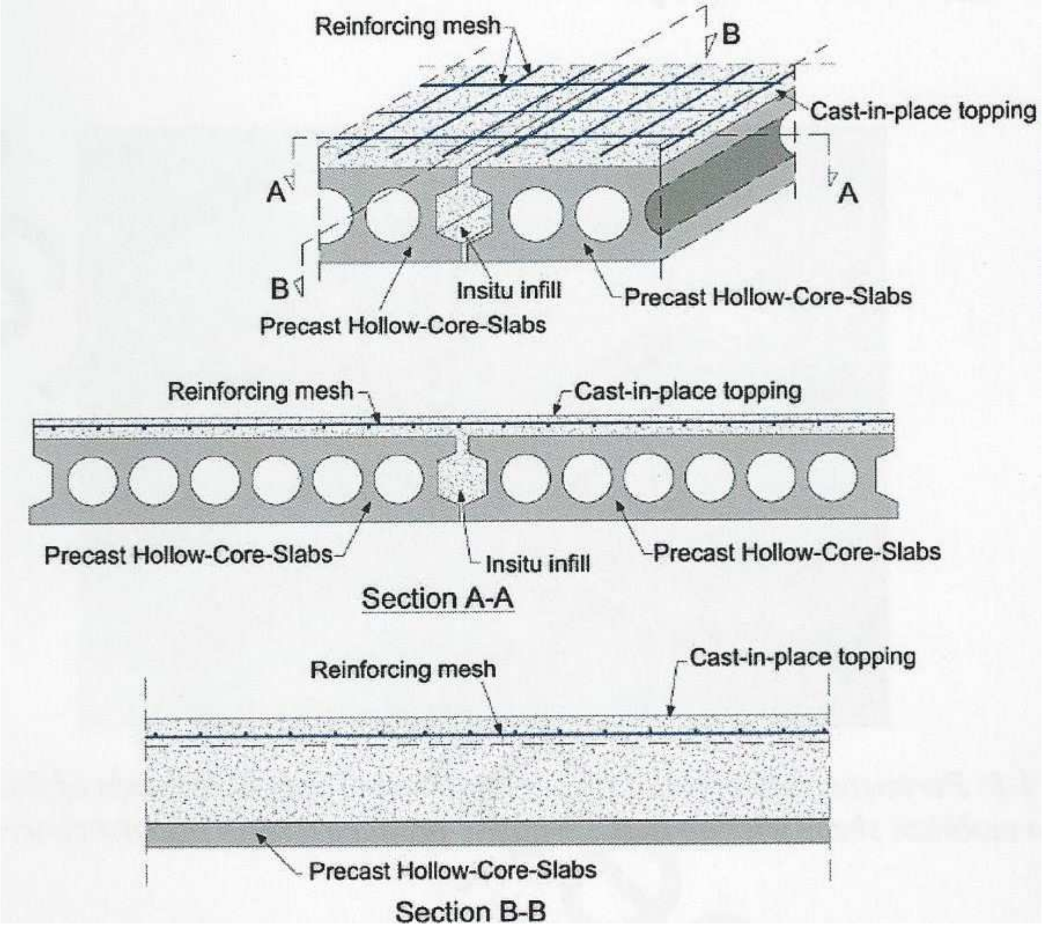


By profilating the edges of the hollow core slab the shear resistance is raised to category 4 “indented” $c = 0.5$ and $\mu = 0.9$

Failure criteria: - yielding of ties
                         - compression failure of concrete
Capacity can be determined by tests

Increasing the shear capacity of the joints

Applying a structural topping

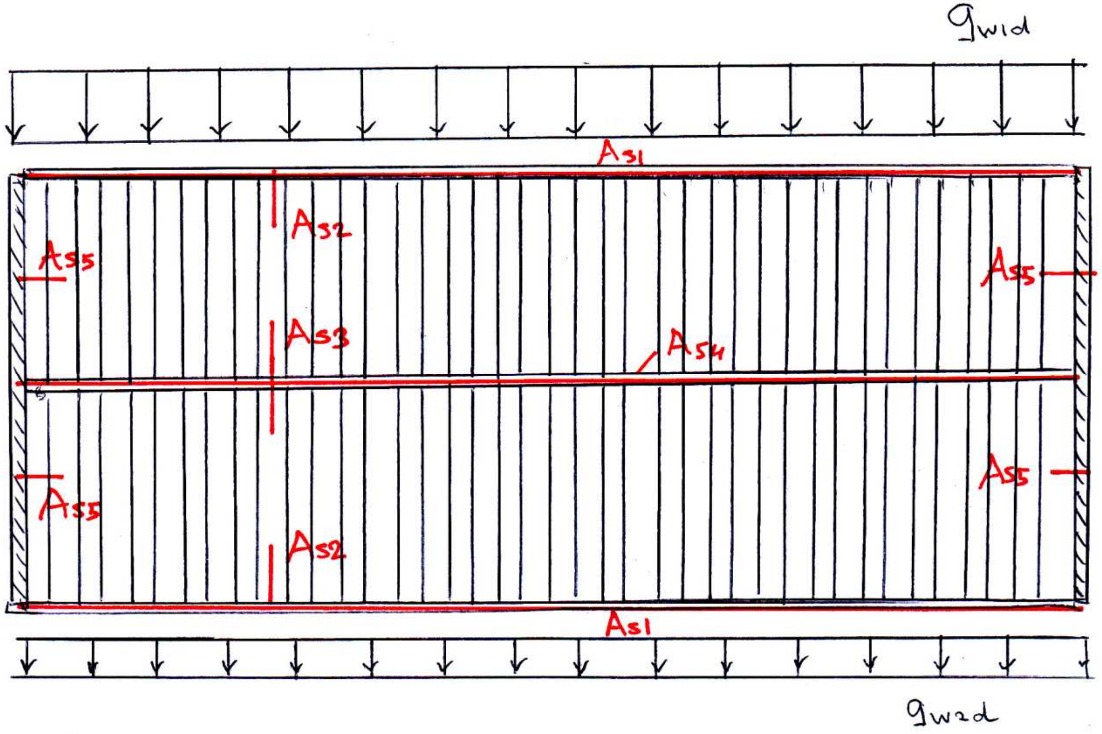


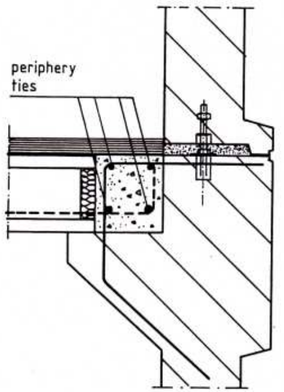
- Thickness reinforced topping ≥ 50 mm
- Function: precast element provides restraint against compressive forces and buckling. Topping takes care of shear across the joints

Summary of functions of reinforcement

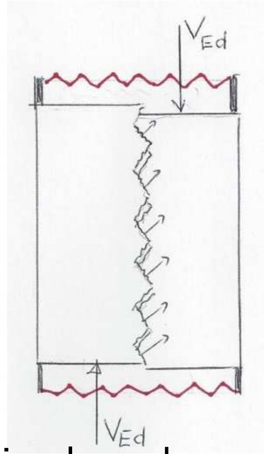
A_{s1} - bending resistance of floor in-plane

- shear resistance of joints in-plane
- shear resistance of joints out of plane



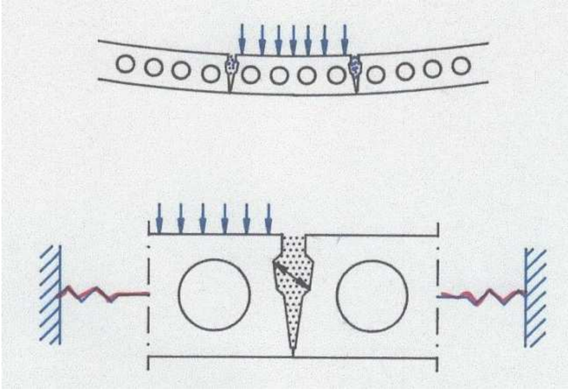


in-plane
bending



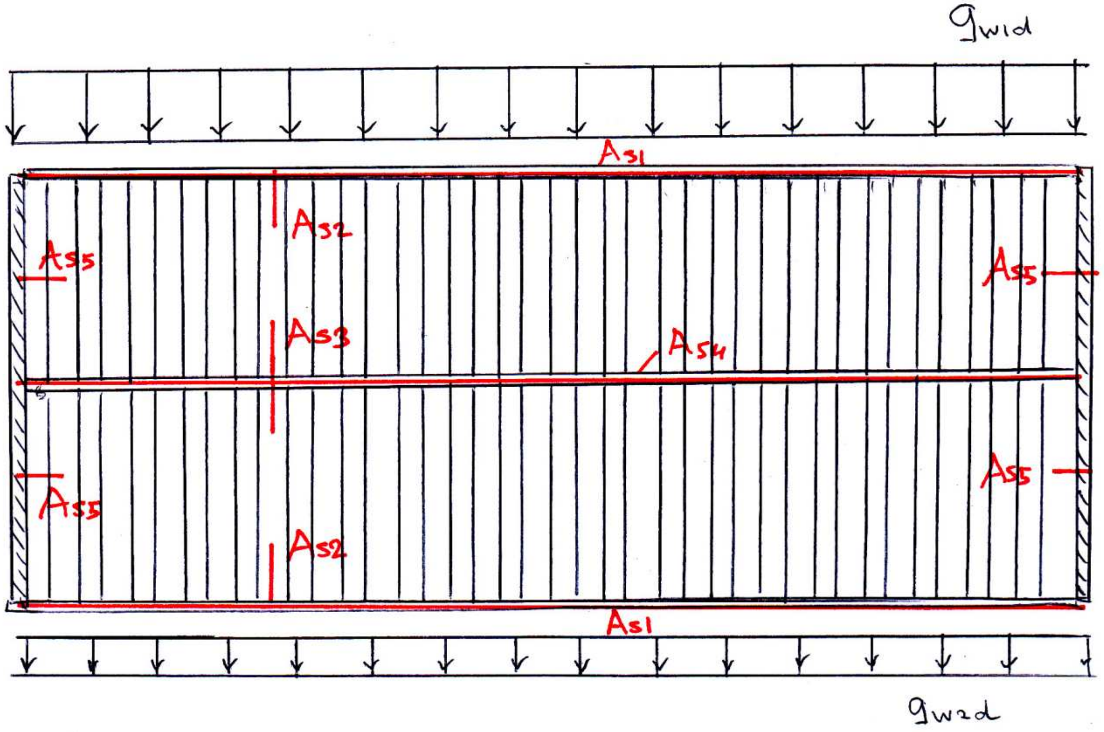
in-plane shear

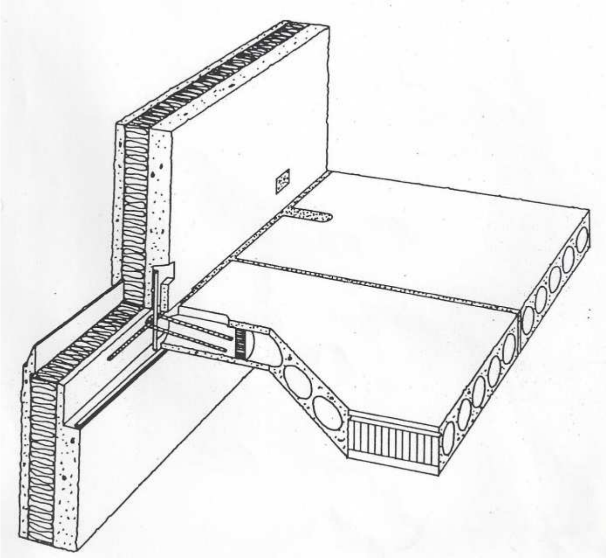
Out of plane shear



Summary of functions of reinforcement

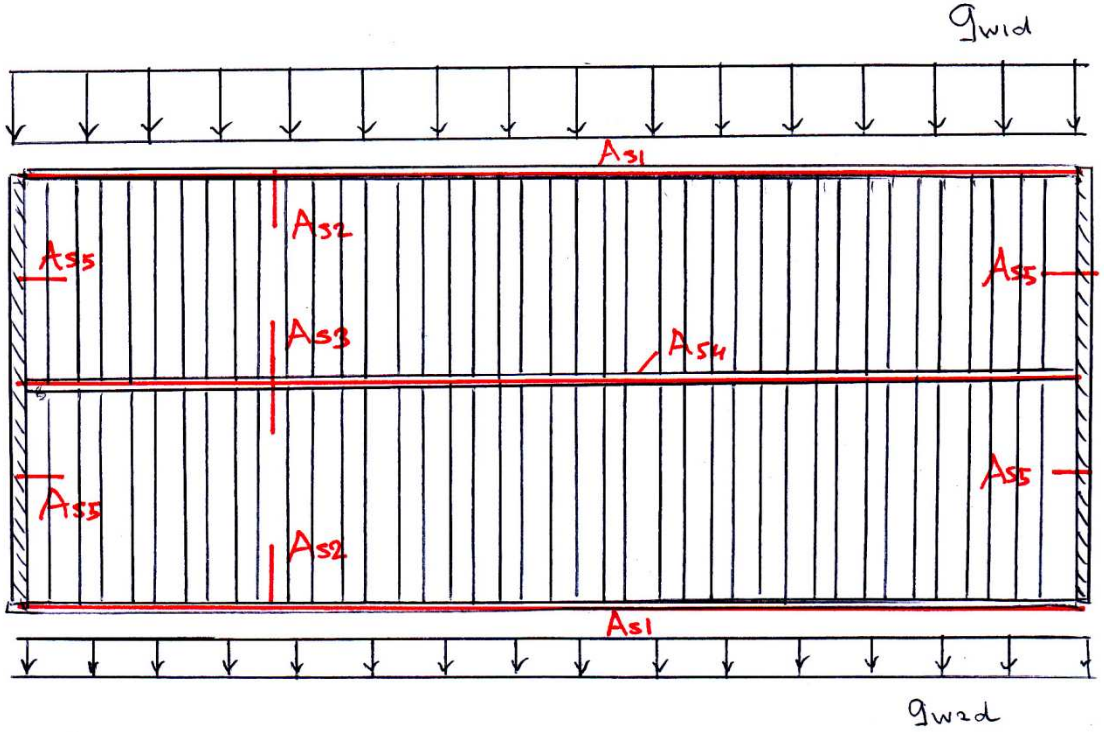
A_{s2} - suspension reinforcement for wind tension load
- robustness of support

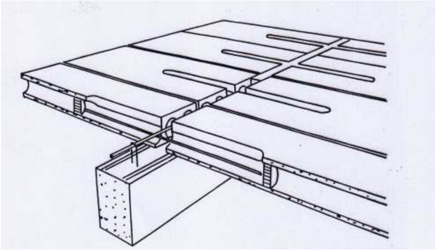


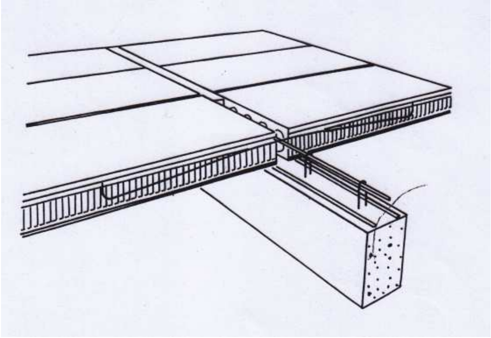


Summary of functions of reinforcement

A_{s3} - suspension reinforcement
- robustness of intermediate support

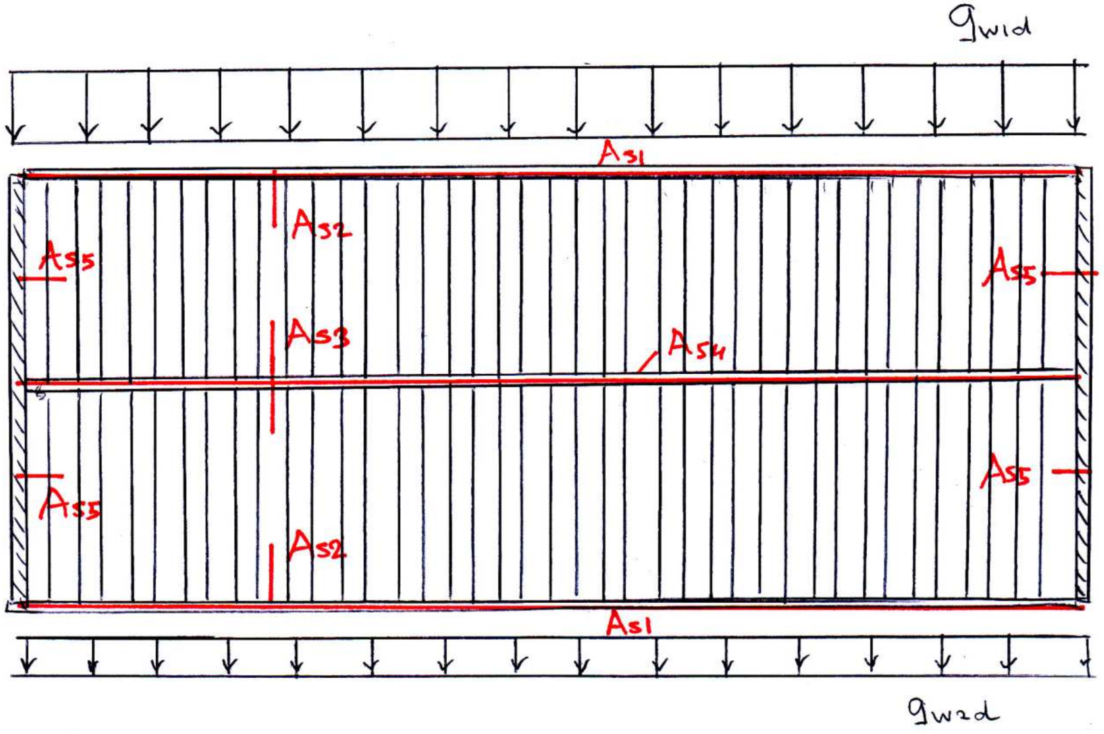


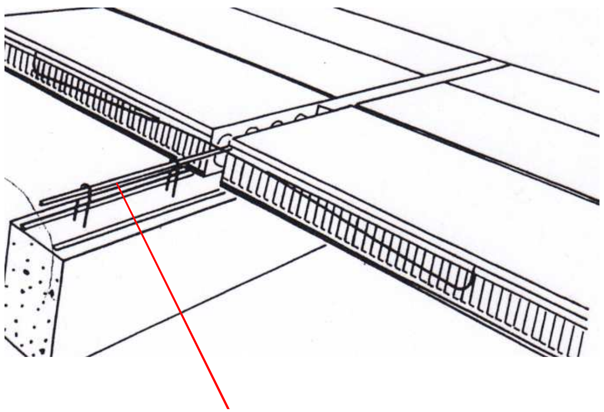




Summary of functions of reinforcement

A_{s4} - in-plane shear capacity of longitudinal joints
- out of plane shear capacity of longitudinal joints
- eventual tensile tie for arch

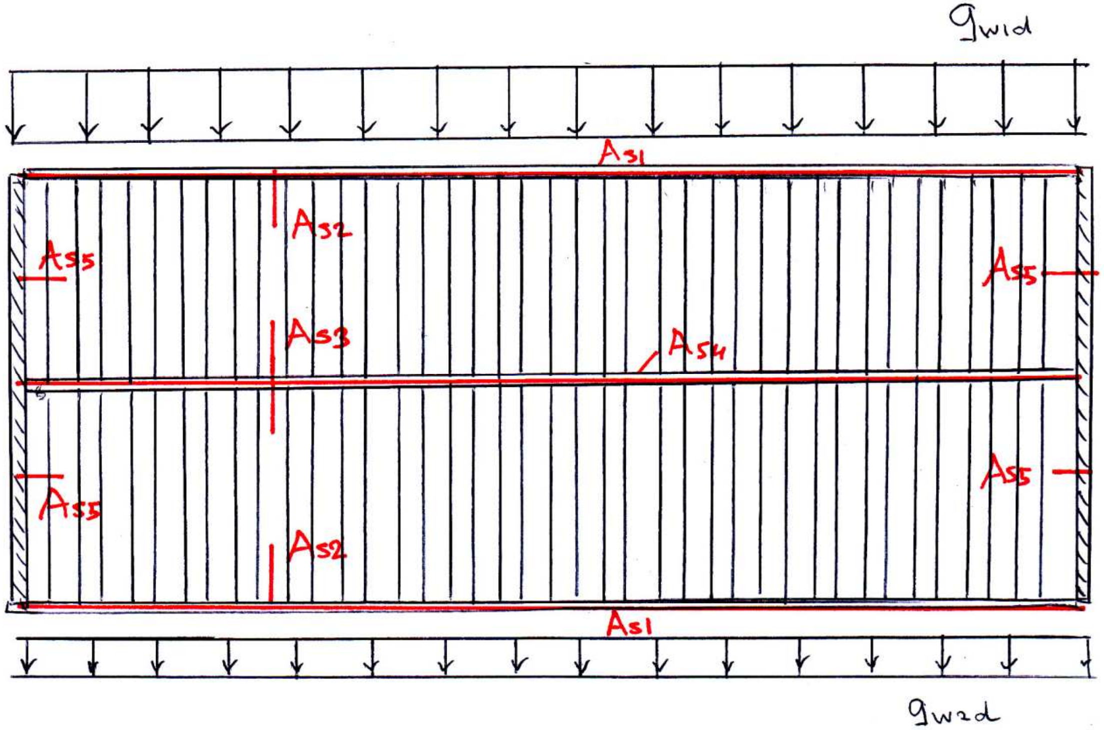




Tensile tie A_{s4}

Summary of functions of reinforcement

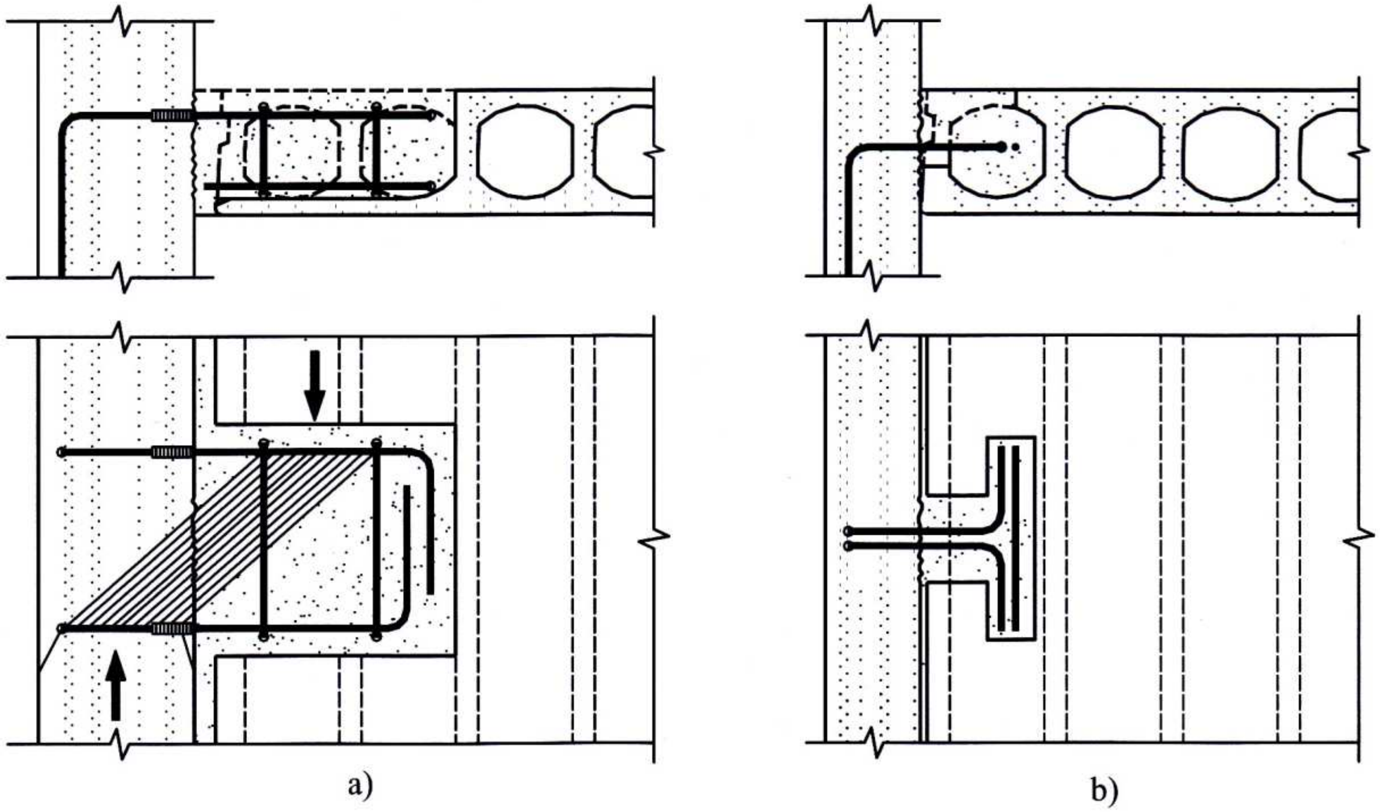
A_{s5} - transmission of horizontal loads from floor to stabilizing walls



Shear connectors A_{s5}

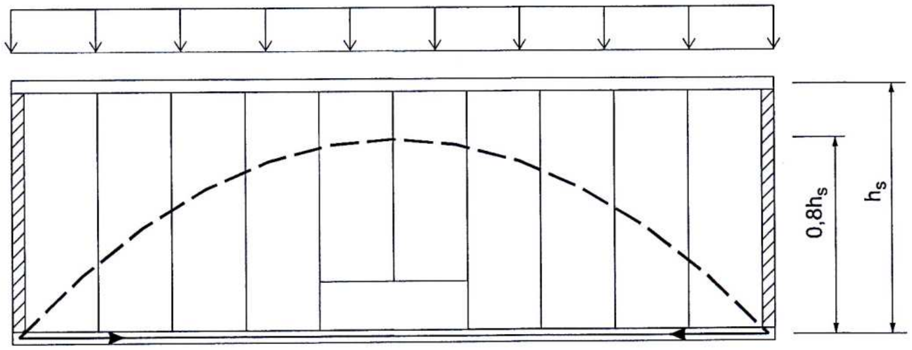
Summary of functions of reinforcement

A_{s5} Further details about shear connector

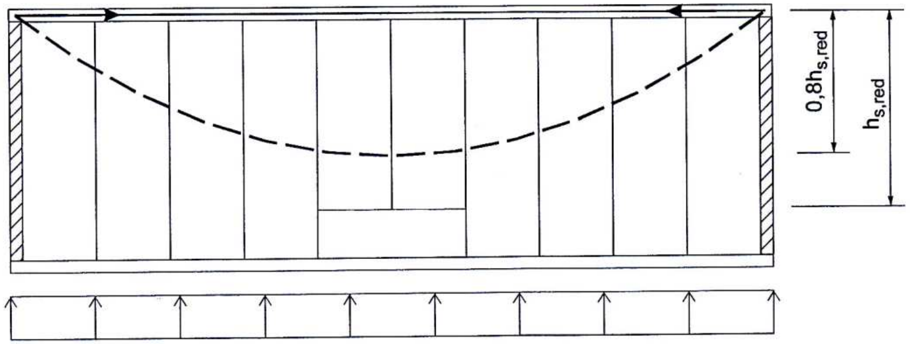


General design considerations

Choice of the correct load bearing model



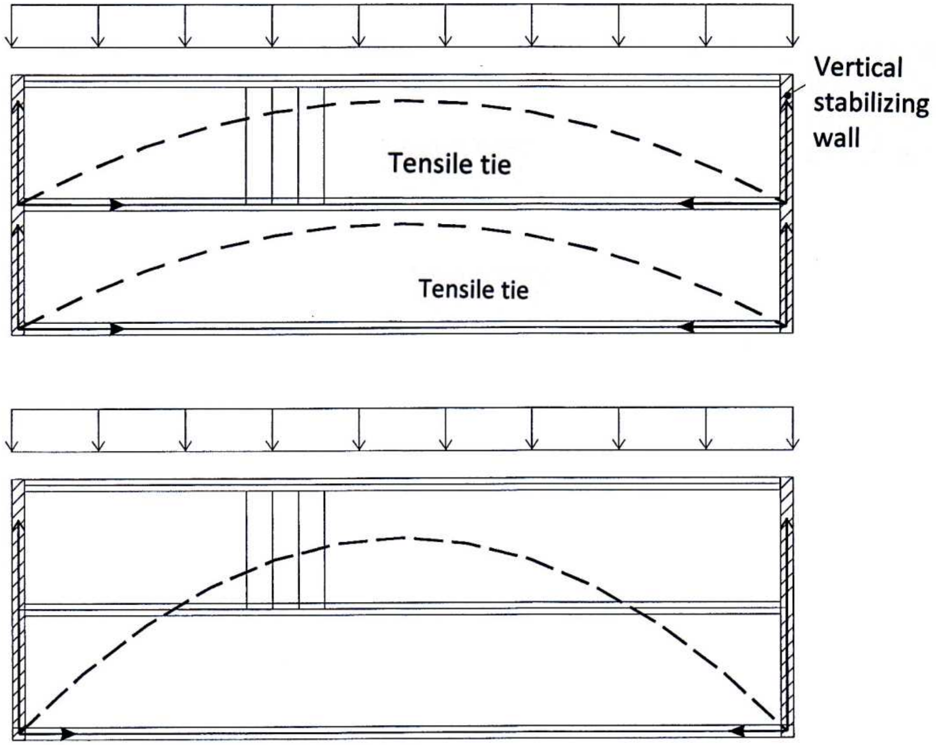
Diaphragm with opening:
For wind from the most favourable side an inner lever arm $z = 0{,}8h_s$ applies.



For wind from the other side the lever arm should be reduced to $z = 0{,}8h_{s,red}$

General design considerations

Choice of the correct load bearing model

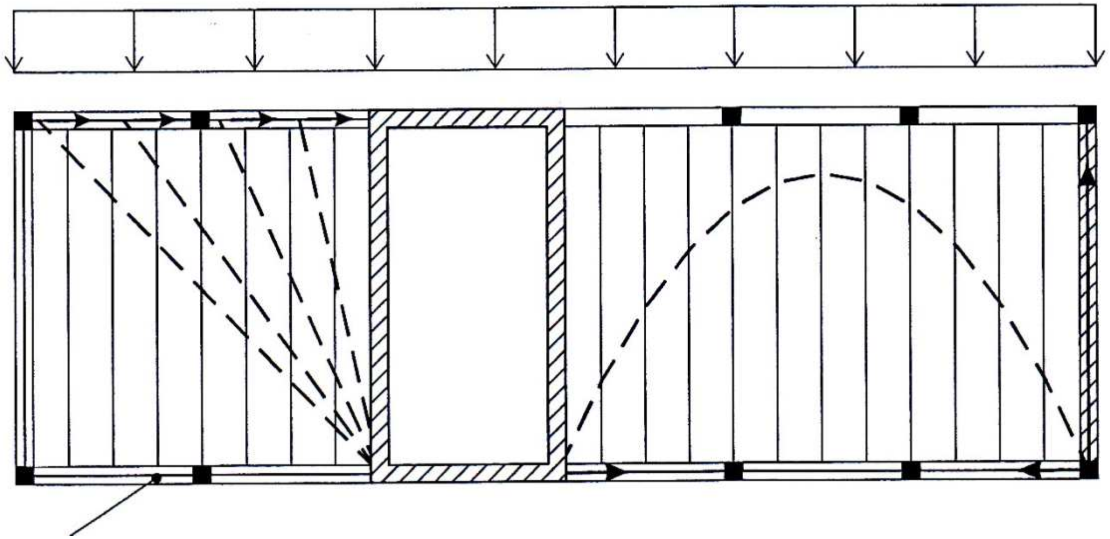


Two options for bearing Mechanism:

- 2-arch system
- 1 arch system with larger inner lever arm

General design considerations

Choice of the correct load bearing model

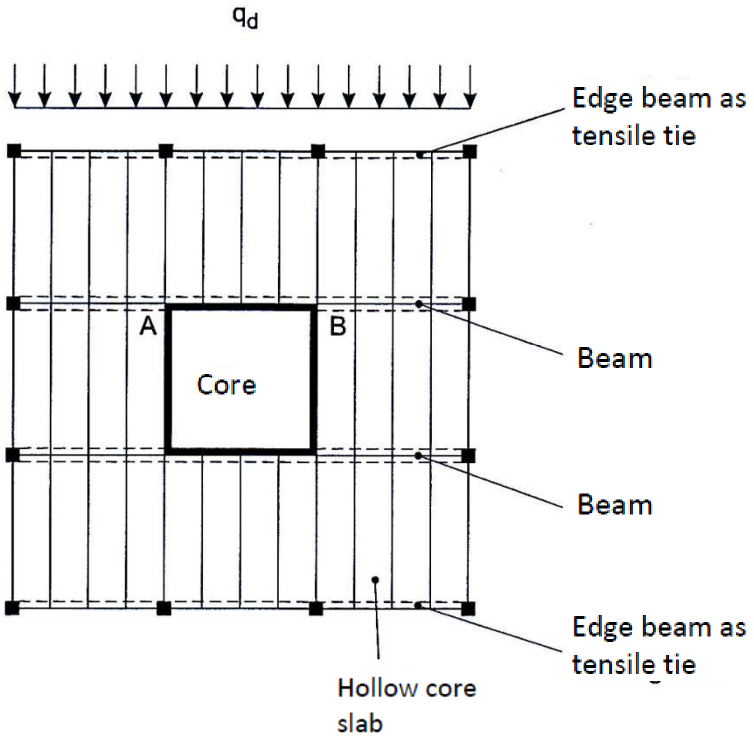


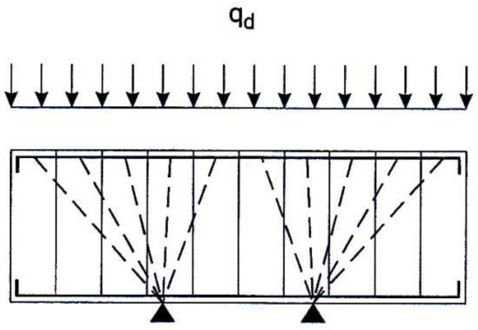
Left side: solution with strut and tie model

Right side: solution with arch

General design considerations

Choice of the correct load bearing model

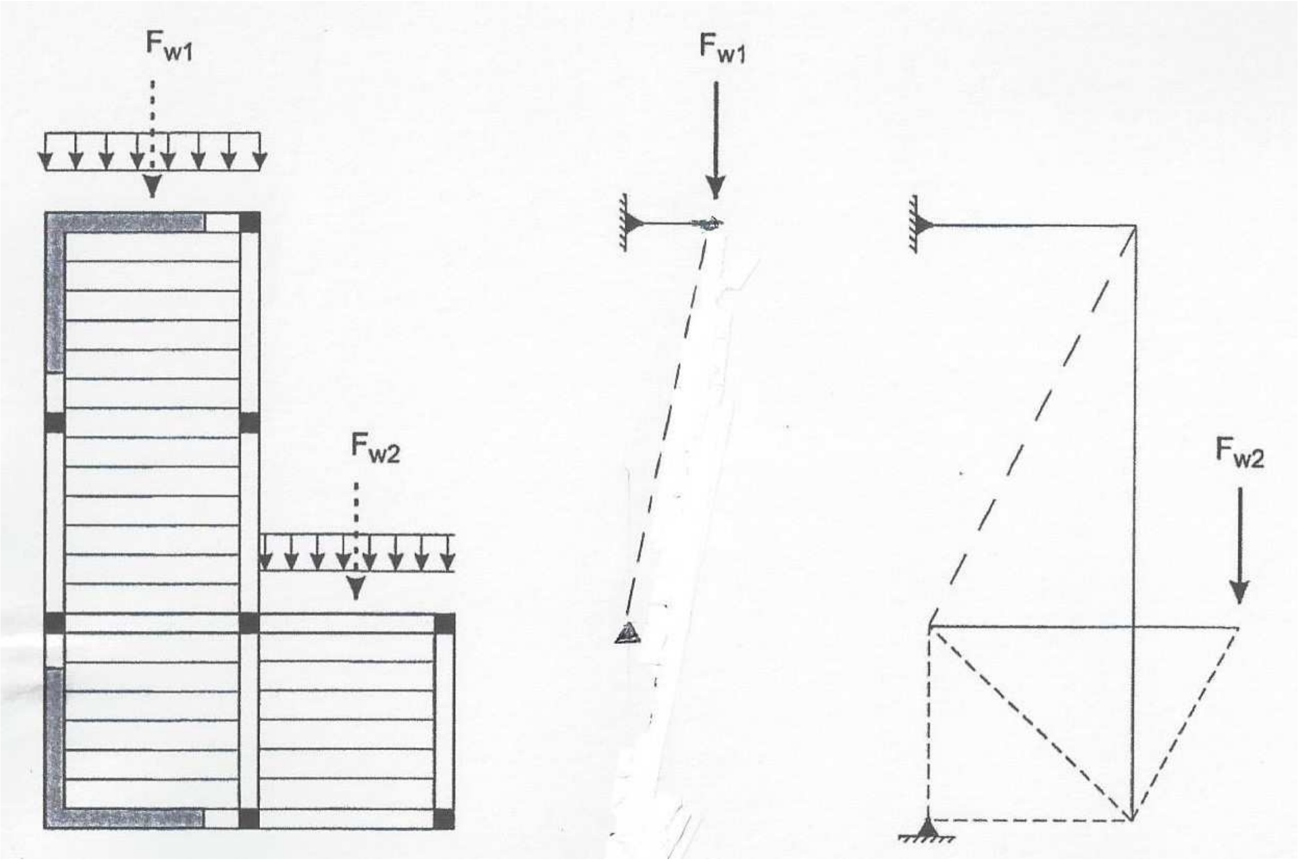




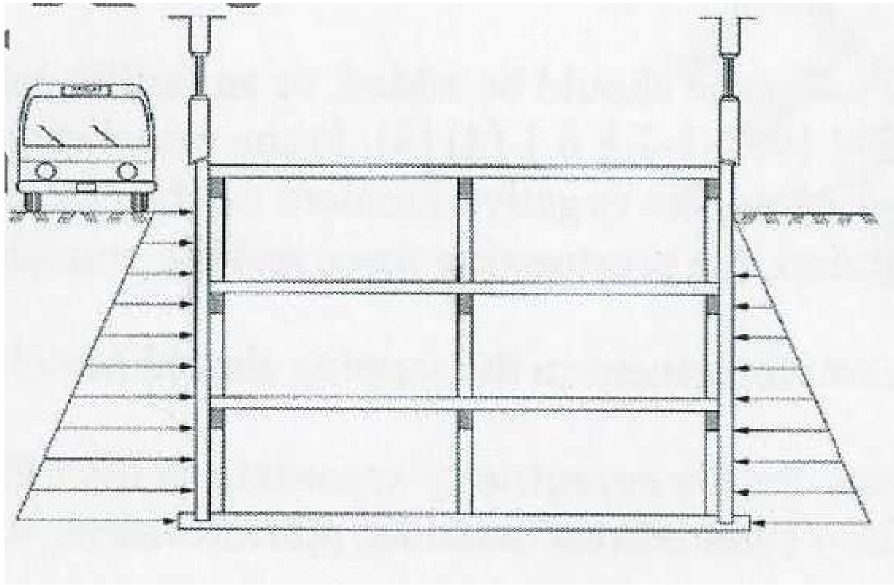
Load resisting model

General design considerations

Choice of the correct load bearing model (strut and tie)



Hollow core floors subjected to horizontal action

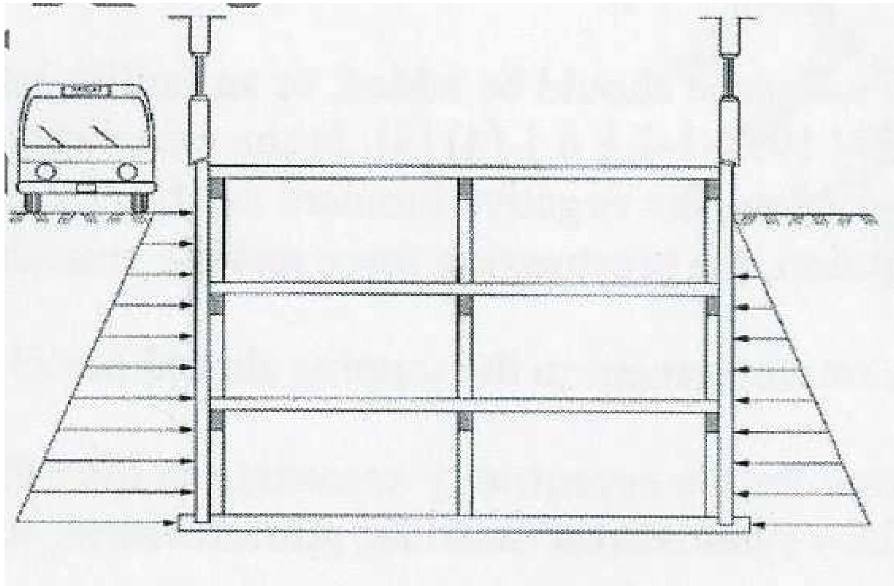


Underground parking house

Floors with two functions:
- carrying the traffic load
- resisting the horizontal soil pressure

Slabs to be designed for buckling

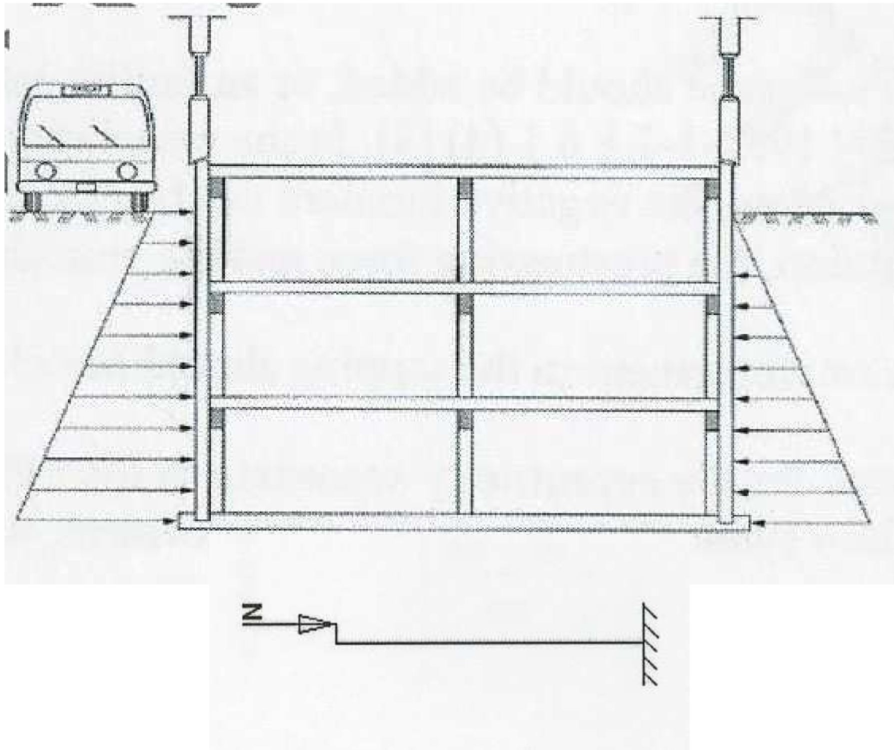
Hollow core floors subjected to horizontal action



To be regarded:

- out of plane deformations of the slab occur due to prestressing, horizontal and vertical loads to be regarded for buckling capacity
- the resist buckling the slab should be designed at two sides: therefore a reinforced structural topping is provided.
- the floor should be checked in the two principal directions
- buckling could occur in upwards and downward direction
- also long term deformations should be regarded

Hollow core floors subjected to horizontal action



Structural system to calculate second order moments for downward buckling

Hollow core floors subjected to horizontal action

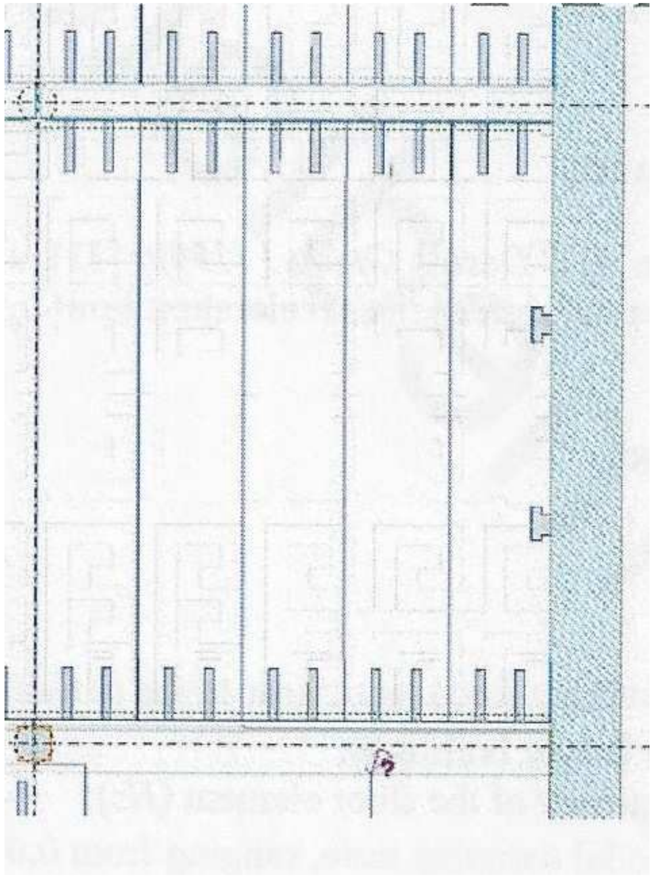
- First calculate the deflections of the unit without axial load by the soil both for short and long term, in upward and downward direction
- Add a tolerance, or an initial camber of 20 mm as requested by EN 1992-1-1, Cl. 6.1(4)
- Calculate the bending moments including the eccentric normal force by the soil, the prestressing force and the vertical loads
- Calculate the reinforcement necessary for the structural topping
- Calculate the additional deflection due to the normal force by the soil
- Follow a stepwise calculation: in any step the additional eccentricities will become smaller (in a good design)
- In a few steps the final situation is found with the governing moments, due to second order effect.
- The final total moment should be checked against the capacity of the slab. If necessary, some prestressing strands should be added

Hollow core floors subjected to horizontal action

Verification in the other direction:

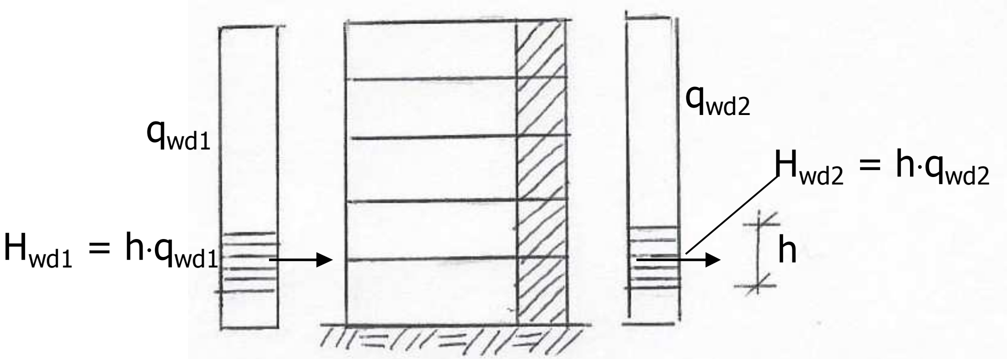
The buckling effects logically only occur in the supporting beams

The axial loads in the beams should be calculated regarding the stiffness of the walls



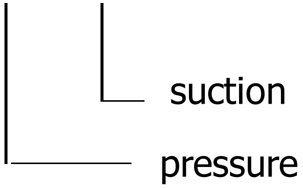
Regarding second order effects in floors without structural topping

Wind

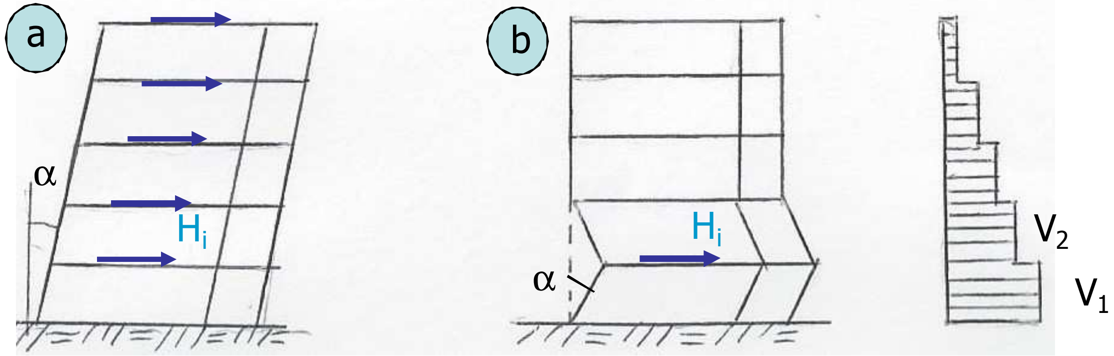


Wind force per floor (per m′ width)

$$H_{wd} = h \cdot q_{wd} \, (c_1 + c_2)$$



Imperfections (inclination)



$H_i = \alpha(V_1 - V_2)$

$H_i = \alpha(V_1 + V_2)$

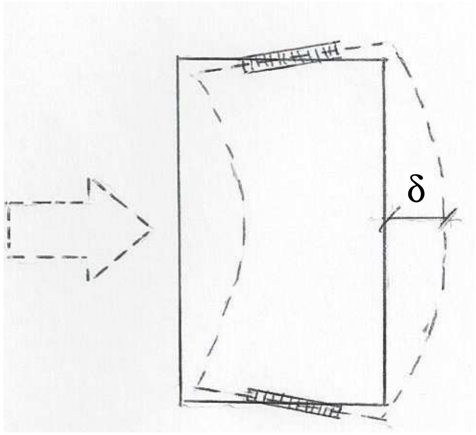
α = code value, depending on number of vertical elements working together per floor

Case ⓐ mostly decisive for stabilizing parts (walls, core)

Case ⓑ mostly decisive for individual floors

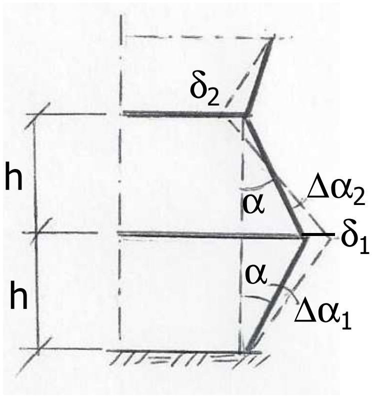
Regarding second order effects in floors without structural topping

Horizontal load
(schematic)



δ = displacement due to horizontal load on floor (wind and imperfection), due to bending

(decrease of bending stiffness due to joint opening to be taken into account (next sheet)



δ_1 = deflection caused by ($H_i + H_w$)

δ_2 = deflection caused by ($H_i - H_w$)

$\Delta\alpha_1 = \delta_1/h$

$\Delta\alpha_2 = (\delta_1+\delta_2)/h$

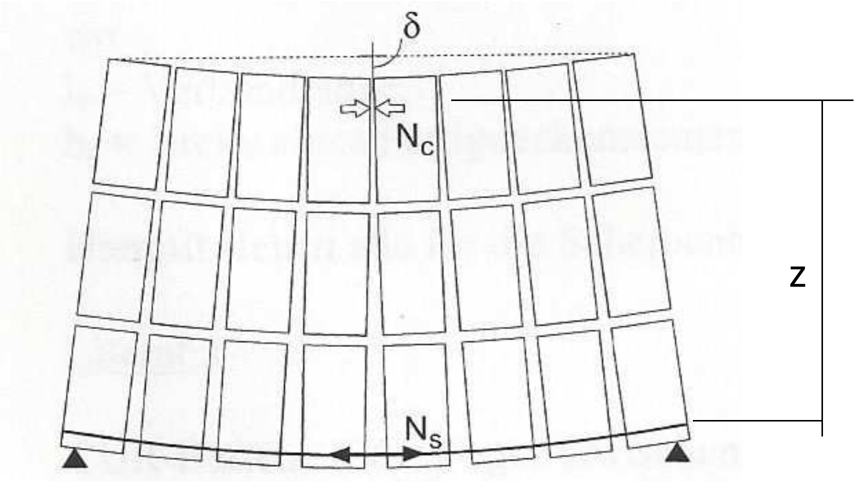
$\Delta H = \Delta\alpha_1 \cdot V_1 + \Delta\alpha_2 \cdot V_2$ (increase of horizontal load on slab (first step in second order calculation)

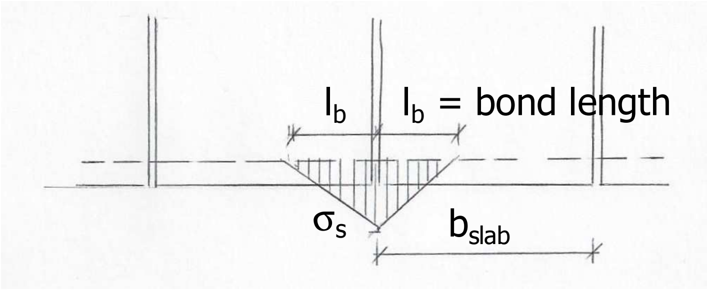
$k_1 = \Delta H/H$

magnification factor $f = 1/(1 - k_1)$

Regarding second order effects in floors without structural topping

Determination of bending stiffness of floor regarding joint opening





Steel stress in joint under moment M :

$\sigma_s = M/(z \cdot A_s)$

Steel strain in joint $\varepsilon_s = \sigma_s/E_s$

Mean steel strain in tensile tie: $\varepsilon_{sm} = (l_b/b_{slab})$

Mean curvature under moment M: $\kappa = \varepsilon_{sm}/z$

δ to be calculated by integration of κ over length of floor

Hollow core slabs as a basic element for beautiful buildings